HIGH Q LINEAR CONTROLLED VARIABLE CAPACITOR USING TRANSLINEAR AMPLIFIER

RELATED PATENT APPLICATION

This application is related to US Patent Application Serial No. 10/764920 filed concurrently herewith on Jan. 26, 2004 and US Patent Application Serial No. 10/676919 filed Oct. 1, 2003, now issued as US Patent 6,937,098, and assigned to the same assignee as the present invention.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

The invention relates to a voltage controlled variable capacitor, and more particularly, to a variable capacitor, formed of a larger number of fixed capacitor segments and a corresponding number of switching elements, which are typically integrated with the capacitance controlling functions on an integrated semiconductor circuit.

(2) Description of Prior Art

One example of a voltage-controlled capacitor is a varactor diode. When a reverse voltage is applied to a PN junction, it creates a depletion region, essentially devoid of carriers, which behaves as the dielectric of a capacitor. The depletion region increases as reverse voltage across it increases; thus the junction capacitance will decrease as the voltage across the PN junction increases. However the characteristics are non-linear and are widely temperature and process dependent. There is also a significant leakage current problem. Varactor diodes must be operated below the junction breakdown voltage. The varactor diode is sometimes called a varicap.

Fig. 1a shows the principle of a varactor diode; **Fig. 1b** shows the control voltage to capacitance characteristics of said varactor diode and demonstrates the effects of temperature and process variations. Another example is a switched capacitor chain, where capacitors are switched in parallel one after the other, thus increasing the capacitance step by step. The capacitors, when made of metal or polycarbonate structures, are far less sensitive to temperature and process deviations.

Fig. 2a shows the basic circuit concept. However, as is demonstrated in **Fig. 2b**, there is only a "step-wise linear" capacitance change over the control voltage. In addition the switching of the individual capacitors causes switching noise ("spikes") on the common circuit rails. Furthermore, while the switching transistor is kept in flat switching ramp to smooth the switching steps, the transistor's resistance causes a Q-factor problem.

U.S. Patent 6,356,135 (to Rastegar) describes an electronically trimable capacitor having a plurality of branch circuits, each including a capacitor which may be selectively controlled by a switch to contribute or not to the net capacitance exhibited by the trimable capacitor. Operation of the switches is under direction of digital instruction.

U.S. Patent 5,514,999 (to Koifman , et al.) shows a differential switched capacitor circuit, comprising: multiple switched capacitor stages, coupled in a chain.

U.S. Patents 4,449,141 and 4,456,917 (to Sato, et al.) disclose a variable capacitor comprising a plurality of variable capacitor elements each having depletion

layer control sections and a capacity reading section formed on a semiconductor substrate so that the capacity appearing at each capacity reading section varies in response to the bias voltage applied to the depletion layer control sections.

SUMMARY OF THE INVENTION

A principal object of the invention described in the present document is to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage. A fundamental requirement is to achieve a high Q-factor at the same time.

The basic aspects of a mechanism to linearly control the capacitance of a variable capacitor in a linear mode through a tuning voltage are described in a related patent application. This related patent application, which is entitled "High Q linear controlled variable capacitor" US Patent Application, Serial No. 10/764920, filed Jan. 26, 2004), is hereby incorporated by reference.

In accordance with the objectives of this invention, a circuit to implement a voltage controlled variable capacitor, operating in a linear mode and maintaining High Q-Factor is achieved. The invention disclosed in the referenced patent application (US Serial No. 10/764920) added circuits and methods to linearize the capacitance change and to minimize the effect of parasitic resistance in the capacitor switching elements, which would degrade Q-factor. The herewith disclosed invention further implements a

translinear amplifier and adds additional circuits to further reduce the effect of parasitic resistance and of temperature deviation.

In the same way as described in the referenced patent application (US Serial No. 10/764920), within a set of small capacitors, one capacitor after the other is switched in parallel to change the total sum of capacitance. To achieve a linear capacitance change, said capacitors are not switched on one by one in digital steps, however each capacitor is switched on partially in a sliding operation, starting at low value (0 % of its capacitance) and ending with the fully switched on capacitor (100 % of its capacitance), i.e. the capacitor is switched on with increasing (or decreasing) share. To achieve said sliding switch operation, a typical implementation uses FET- type transistors as switching device, one per capacitor. The switching operation of such FET-type transistor can be divided into three phases: the fully-switched-off phase (said FET transistor's drain-source-resistance RDS is very high), a steady ramp-up/ramp-down phase or steady transition phase (that is: said FET transistor's resistance RDS is changing between very high resistance and very low resistance in a linear and steady mode) and the fully-switched-on phase (said FET transistor's drain-source-resistance RDS is very low). By thoroughly controlling such switching device within said linear and steady ramp-up/ramp-down phase, the capacitor in series with said switching device is partially switched in parallel with a well-controlled proportion between 0 % and 100 %.

The terms "steady ramp-up/ramp-down phase" or "steady transition phase" (and "steady ramp-up/ramp-down area" or "steady transition area") are used as synonyms throughout this document. The term "area" in this context is used to express the

"operating range" – the term "phase" is used to express the "operation in process" within said area.

One key point to obtain highest possible Q-factor is to have at any time only one (or very few) transistor in the steady transition phase, i.e. RDS changing mode; all other transistors are either fully switched on or fully switched off. To achieve this goal, an individual threshold level for each capacitor switching stage defines the point where, in relation to the tuning voltage, each of said capacitor switching stages switches from the off to the on state. Overlapping of neighboring switching stages cannot be completely eliminated, but overlapping is kept to a minimum by selecting appropriate threshold parameters.

Key element to achieve the goal of the invention is the introduction of a translinear amplifier into the signal path. Furthermore, functions to limit the switching-signal in order to drive the capacitor-switching element, typically a FET-transistor, into minimum RDSon or maximum RDSoff are added. Even further, a circuit to compensate the temperature effect of the capacitor switching device is added.

The translinear amplifier, typically with a gain of 1, compares a differential voltage at its inputs and provides the same differential voltage at its outputs; i.e. the output difference of said amplifier strictly follows the difference at said amplifier inputs, independent of the absolute voltage level at the outputs; input and output are perfectly decoupled. Said translinear amplifier can operate at different absolute voltage levels at

their input and work independent at an output level, best suitable for said switching transistor's operation.

While the switching transistor is kept within its steady transition phase (RDS steady changing mode) the resistance of said switching transistor linearly follows the input difference of said translinear amplifier. As said translinear amplifier can operate at different absolute voltage levels at their input and output, the resulting level shifting operation is best suitable for said switching transistor's operation.

Additional circuit elements, described in the related US Patent Application, Serial No. 10/676919, filed Oct. 1, 2003, titled "Translinear Amplifier" and hereby incorporated by reference, implement a signal cutoff function by providing a signal to sharply cut off said translinear amplifier's linear operation, once the defined linear operating range is exceeded at the negative end of said linear operating range; and to sharply limit said translinear amplifier's linear operation, once the linear operating range is exceeded at the positive end of said linear operating range. The circuits of said signal cutoff functions then either takes over control of said switching transistor to either drive it into deep saturation (RDSon going to 0) or drive it into its extreme off state (RDSoff going very high), when said switching device operates outside its desired steady transition phase.

There are various techniques to generate a set of reference values defining the threshold levels for the input and output reference levels of each of said translinear

amplifier stages. And there are various techniques to provide a tuning voltage, dedicated for the voltage controlled capacitance change, to all of said amplifier stages.

The total concept according to the proposed invention is shown in **Fig. 6**. One key point of the invention is the implementation of signal cutoff functions at both ends of the steady ramp-up/ramp-down phase. Once the signal controlling the switching device leaves the steady transition phase, the signal condition is changed abrupt. **Fig. 7b** visualizes this effect. The purpose is to drive said switching device to a fully-on state, when said switching device operates outside its steady transition area on the low resistance side (low RDSon) of said switching device and, in a complementary way, to drive said switching device to a fully-off status, when said switching device leaves its steady transition area on the high resistance side (high RDSoff).

Depending on the technique to implement the reference values for each of the translinear amplifiers within a chain of said capacitor switching stages, even specific nonlinear relations of capacitance change versus tuning voltage can be constructed.

In accordance with the objectives of this invention, a set of individual capacitors is implemented. Such capacitors could, for example, be discrete metal or polymer capacitors on a common planar carrier or they could be integrated on a semiconductor substrate. The switching device is typically a FET transistor, which could be for example a P-channel or N-channel junction FET or a PMOS or NMOS FET.

The amplifier primarily generating the control signal for the switching devices is, according to the invention, a translinear amplifier, as described in patent application, US

Serial No. 10/676919, filed Oct. 1, 2003. In addition, signal cutoff functions, which are designed to drive said switching device to a fully-on status, when said switching device operates outside its steady transition area on the low resistance side (low RDSon) or to drive said switching device to a fully-off status, when said switching device operates outside its steady transition area on the high resistance side (high RDSoff), can be implemented. Such signal cutoff functions could, according to the invention, be implemented with additional circuit elements within the translinear amplifier. They could however be implemented as separate circuits as well.

The circuit also provides the components to generate the set of reference voltages for the threshold levels of each capacitor switching stage. A resistor chain is one possible solution. The amplifiers within each capacitor switching stage then use the tuning voltage supplied and said reference voltages to generate the control signal for said switching devices, which then switch the capacitors in parallel, one after the other.

Furthermore, the temperature deviation, caused by the temperature characteristics of the switching device can be compensated. One concept is to use a device of the identical type of the switching device to produce a temperature dependent signal and feed it as compensating voltage into the output reference point of the translinear amplifier. This will mirror the exact equivalent of the temperature error into the switching control signal and compensate its temperature error. Details of a possible implementation are provided in the related patent application US Serial No. 10/676919.

Even further, a specific non-linear characteristic of the tuning voltage to capacitance relation can be achieved by dimensioning the relation between said tuning voltage and said individual threshold levels as desired. In one proposed solution, the individual steps of the reference resistor chain will be dimensioned to a desired nonlinear curve, for example when the steps between the threshold levels, where the next capacitor starts to be switched on, are narrower in one area than in other areas, more capacitors start to be switched in parallel and a steeper change of total capacitance can be achieved. .

A translinear amplifier typically has a gain of 1. However, a gain different from 1 is also achievable, which, if implemented, gives one more degree of freedom in dimensioning and optimizing certain operating parameters. For example, the remaining overlapping of neighboring capacitor switching stages may be even further reduced, as the steepness of the steady ramp-up/ramp-down operation can be controlled with adequate selection of the gain.

In accordance with the objectives of this invention, a method to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage and to achieve a high Q-factor at the same time generate, is achieved. One method is to switch a variable number of capacitors in parallel, where only one is in the steady transition phase of being switched on (or off) in a steady progressing mode (i.e. the effective capacitance being ramped-up or ramped-down). All other capacitors of a larger number of capacitors are either already fully switched on or are still complete switched off. One key method is to linearly control the switching function for each of

said switching devices, when said switching device is in an analog mode within the steady transition phase but to change the signal abrupt, as soon as the control signal for said switching function leaves its steady transition area. One method drives said switching device to a fully-on status, when said switching device operates outside its steady transition area on the low resistance side. A similar method drives said switching device to a fully-off status, when said switching device is beyond its steady transition area on the high resistance side. A further method amplifies, by a translinear amplifier, the difference of the capacitance tuning voltage and the reference voltage of each amplifier stage, producing the linear control signal for said steady progressing switching operation. Another method generates a set of reference values, one for each of said amplifier stages. Finally, the circuit supplies a tuning voltage, dedicated for the voltage controlled capacitance change, to all of said amplifier stages.

A further method compensates the temperature effect of the switching device. It generates a temperature dependent compensation voltage by using an identical device-type as the switching device and feeds the resulting signal into the output reference point of the translinear amplifier.

An even further method is to produce threshold levels along a non-linear curve, i.e. by not spreading said threshold levels with equal distances in order to get a desired non-linear relation of the total capacitance change versus tuning voltage.

BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings, forming a material part of this description, there is shown:

Fig. 1a (Prior Art) shows a simplified structure of a varactor diode.

Fig. 1b (Prior Art) shows the relation of the capacitor over tuning voltage change and shows the effects of temperature and process variation.

Fig. 2a, and 2b (Prior Art) shows a principal circuit of a switched capacitor chain and the relation of the capacitor over tuning voltage change.

Fig. 3 shows a circuit with operational amplifiers in the control signal path and with a chain of resistors as reference voltage circuit.

Fig. 4a shows the gate voltage versus tuning voltage relation for the chain of capacitor switching stages, according to Fig. 3.

Fig. 4b visualizes the signal overlapping effect of the switching operations of just 2 stages of the circuit according to Fig. 3.

Fig. 4c visualizes the reduced signal overlapping effect of 2 adjacent stages with steeper control signals.

Fig. 5 shows the principal circuit arrangement of a single capacitor switching stage with a translinear amplifier.

Fig. 6 shows the circuit schematic of multiple capacitor switching stages, each comprising a translinear amplifier, in accordance with an embodiment of this invention.

Fig. 7a shows the relation of a switching device's resistance RDS versus its gate voltage.

Fig. 7b visualizes said switching transistor's gate voltage versus capacitor tuning voltage dependency of a single stage.

Fig. 8 visualizes said switching transistor's gate voltage, versus capacitor tuning voltage dependency of a multiple stages.

Fig. 9 shows a realistic circuit diagram of an implementation, in accordance with an embodiment of this invention.

Fig. 10a shows the additional circuits to provide the cutoff signals to drive the switching devices to a fully off or fully on state.

Fig. 10b shows a circuit added to modify the reference voltage for temperature compensation.

Fig. 10c shows an added circuit to generate a temperature compensated reference voltage.

Fig. 11a demonstrates the resulting capacitance versus tuning voltage for multiple capacitor switching stages, according to Fig. 6.

Fig. 11b demonstrates the resulting Q-factor versus tuning voltage for multiple capacitor switching stages, according to Fig. 6.

Fig. 12 demonstrates 2 possible variations of capacitance versus tuning voltage characteristics.

Fig. 13 visualizes the methods to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage and achieving a high Q-factor.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The objectives of this invention are to control the capacitance of a variable capacitor in a strictly linear mode through a tuning voltage. A fundamental requirement is to achieve a high Q-factor at the same time.

A discussion of the general principles of a voltage controlled variable capacitor with linear characteristic, formed of a larger number of fixed capacitor segments and a corresponding number of switching elements, using operational amplifiers is disclosed in the related US Patent Application Serial No. 10/764920, filed Jan. 26, 2004, the entire contents of which is incorporated herewith by reference.

Fig. 3 shows a principal circuit diagram of the referenced related patent application. A set of circuits to control the switching operation in a ramp-up/ramp-down manner, contains, typically besides other components, the set of operational amplifiers **Amp 1** to **Amp n**. **Sw 1** to **Sw n** are said switching devices and **Cap 1** to **Cap n** are said capacitors that will be switched in parallel. As an example, a resistor chain **R1** to **Rn**, or a similar circuit, produces a series of voltage references **Ref 1** to **Ref n** and each of said operational amplifiers compares the tuning voltage input with its dedicated reference voltage. The resulting variable capacitance is available at the output connector **varCap**. As a minimum circuit implementation, a simple wire connection feeds the tuning voltage directly to the amplifier inputs.

The herewith disclosed invention replaces said operational amplifiers of the referenced related patent application Serial No. 10/764920 with translinear amplifiers, as shown in **Fig. 6**.

According to the objectives of this invention, the operational amplifiers, within said set of circuits to control the switching operation in a ramp-up/ramp-down manner, as shown in **Fig. 3**, are replaced by translinear amplifiers. A single stage of said capacitor switching function is presented in **Fig. 5** and the total circuit schematic for multiple stages according to the proposed invention is shown in **Fig. 6**, where a set of circuits to control the switching operation in a ramp-up/ramp-down manner, contains, typically besides other components, the set of translinear amplifiers. Key advantage is the fact, that the voltage levels at the translinear amplifier inputs and at the translinear amplifier outputs are independent, only the differential voltage at the inputs and at the outputs is important. Said translinear amplifier works in this context as a level shifter. Such translinear amplifiers have typically a gain of 1.

The translinear amplifier in **Fig. 5**, imbedded within said circuit to control the switching operation **Switch-Ctrl** compares the differential voltage at its inputs **Vinp-5** and **Vinn-5** and, through various current mirroring techniques, provides the same differential voltage at its outputs **Voutp-5** and **Voutn-5**; i.e. the output difference of said amplifier strictly follows the input difference, independent of the absolute voltage level at the outputs. Similar to Differential Amplifiers, a Translinear Amplifier has differential inputs and has differential outputs. In fact, the outputs are floating together, however the signal **Voutn-5** may also be forced to any desired reference level – then the voltage

at **Voutp-5** will always follow that forced reference level with a difference of **Voutp-5 - Voutn-5 = Vinp-5** - **Vinn-5**. It should be noted at this point, that signal **Voutn-5** effectively operates as an input signal, though it is drawn on the right side of the amplifier symbol, which normally represents output signals - **Voutn-5** operating as an input allows to apply a desired output reference level,

A single capacitor switching stage, as shown in **Fig. 5**, contains a circuit to control the switching operation **Switch-Ctrl** (also called hereafter the switch control circuit), a switching device **SW** and a small capacitor **Cap**. Said circuit to control the switching operation receives a signal, dependent on the tuning voltage **Vtune**, an input reference signal **Ref-in-5** and an output reference signal **Ref-out-5**, where said input reference signal **Ref-in-5** is then provided to the input reference point **Vinn-5** and said output reference signal **Ref-out-5** is then provided to the output reference point **Voutn-5**. The translinear amplifier in **Fig. 5**, imbedded within said circuit to control the switching operation **Switch-Ctrl**, possibly together with some electronic glue components, compares the differential voltage at its inputs **Vinp-5** and **Vinn-5** and provides the same differential voltage at its outputs **Voutp-5** and **Voutn-5**; i.e. the output difference of said amplifier strictly follows the difference at said amplifier inputs, additionally controlled by applying a reference voltage level at output **Voutn-5**. Said switch control circuit **Switch-Ctrl** then provides a switch control signal **Vsw**, based on said translinear amplifier's output signal **Voutp-5** to said switching device **SW**. Switch control signal **Vsw** then drives a current switching device **N1-5** with the gate voltage **Vg-5** to switch on said individual small capacitor **Cap-5** in the proposed steady ramp-

up/ramp-down manner. Switching in said steady ramp-up/ramp-down manner results in the desired variable capacitance **Var-Cap-5** of said single capacitor switching stage.

Each of said translinear amplifiers can operate at a different absolute voltage level at their input and work independent at another output level. In this way the network to generate the reference voltages can be optimized independently for each stage, because the voltage level best suitable for the control operation of each switching transistor can be freely selected. In the circuit shown in **Fig. 6** as an example, a common reference circuit **RefCirc** individually provides the input and output reference voltages to each of said switch control circuits **Switch-Ctrl** with their imbedded translinear amplifiers **Tr.Amp 1** to **Tr.Amp n**, As described with Fig. 5, said translinear amplifiers can individually adjust between said input reference voltage levels **Ref-in 1** to **Ref-in n** and said output reference levels **Ref-out-1** to **Ref-out-n**. Then each of said translinear amplifiers provides its signal to control the switching devices **Sw 1** to **Sw n**, which in turn switch on the individual small capacitors **Cap 1** to **Cap n** in the proposed steady ramp-up/ramp-down manner. Each of said capacitor switching stages connects to one capacitor **Cap k** out of a set of small capacitors. Each of said capacitor switching stages is controlled through the common input signal **Vtune** and an individual input reference **Ref-in k**. All of these stages k = 1 to n have basically identical functional characteristics.

In the same way as described in said related patent application US Serial No. 10/764920, within a set of small capacitors **Cap 1** to **Cap n**, one capacitor after the other is switched in parallel to change the total capacity. Each capacitor has its

individual switching device **Sw 1** to **Sw n.** To achieve a linear capacitance change, said capacitors are not switched on one by one in digital steps, however each capacitor is switched on partially in a sliding operation, starting at low value (0 % of its capacitance) and ending with the fully switched on capacitor (100 % of its capacitance), i.e. the capacitor is switched on with increasing (or decreasing) share. To achieve said sliding switch operation, a typical implementation uses FET- type transistors, one per capacitor. The switching operation of such FET-transistor can be divided into three phases: the fully-switched-off phase (the FET transistor's drain-source-resistance RDS is very high), a steady ramp-up/ramp-down phase or steady transition phase, where the series resistance of said FET-transistor linearly follows the gate voltage and steadily changes from high to low values or vice versa, and the fully-switched-on phase (said FET transistor's drain-source-resistance RDS is very low). **Fig. 10b** in US Patent Application Serial No. 10/764920, included by reference, visualizes the principal RDSon characteristic versus gate voltage of the switching devices **N1-5** of a single capacitor switching stage according to **Fig. 5** of the present application. By thoroughly controlling such switching device within said steady ramp-up/ramp-down or steady transition area, the capacitor in series with said switching device is effectively switched in parallel to the other capacitors with a well-controlled proportion between 0 % and 100 %. "Steady" is meant in the mathematical sense of being free of jumps or breaks. The limits of said steady ramp-up/ramp-down or steady transition area is distinguished by the points, where a further change of the controlling signal of the switch does not lead to further decrease or increase of the series resistance of said switching device (except for a small, negligible change).

In case a specific member of said switching devices, as shown in **Fig. 6**, is switched fully-on, the parallel connection of the capacitor (in series with said switching device in view) is fully effective (i.e. is effective to 100 %). If however a specific item of said switching devices is switched fully-off, the parallel connection of the capacitor (in series with said switching device in view) is not effective at all (i.e. is effective to 0 %). While said switching device in view is operating within its steady ramp-up/ramp-down or steady transition phase, the capacitor may be effectively switched in parallel with any value between 0 % and 100 %. The effectiveness of the switching in parallel of said capacitor is well controlled through the translinear amplifiers **Tr.Amp 1** to **Tr.Amp n** and the relation of tuning and reference voltages, according to the input reference levels provided by the common reference circuit **RefCirc**. One can assume the steady transition area of RDS changing to be, for example, between the 2 % point and the 98 % point and define these limits as the desired end points of the steady transition area. Close to these end points, the linear operation of real switching devices come to a natural end.

The terms "steady ramp-up/ramp-down phase", “steady transition” and "steady transition phase" or "steady transition area" will be used throughout the document as synonyms, defining the phase of analog switching operation (i.e. steady ramp-up/ramp-down) as opposed to a pure digital switching operation (pure on/off). The area where said steady ramp-up/ramp-down is possible, is called the “steady ramp-up/ramp-down area” or “steady transition area”. As said before, "steady" is meant in the mathematical sense of being virtually linear, free of jumps or breaks. In the same sense, the term "continual switching" means the ongoing process of "steady ramp-up/ramp-down

switching". The term "area" in this context is used to express the "operating range" – the term "phase" is used to express the "operation in process" within said area.

The linear operation of real switching devices is naturally limited, for example because it is reaching a switching transistor's saturation or because the resistance already reached the maximum achievable value and where, for example, a further change of gate voltage **Vg** would not create further increase of a switching transistor's resistance RDS. As explained before, the area of linear operation is called the "steady transition area", consequently the areas beyond the linear operating area are named here as the areas "outside the steady transition area". These are the areas where further change of the switch control signal **Vsw** would first cause only a non-linear change of resistance RDS and would finally have no more effect. In **Fig. 7a** the linear operating area and its end-points is shown: the **Steady Transition Area**, the end-point of the steady transition area at the low (RDS) resistance side of said switching device, marked **Ep-Lo**, and the end-point of the steady transition area at the high (RDS) resistance side of said switching device, marked **EP-Hi**.. The switching device to switch on the capacitor is used for the presented patent application as a "switching device with a well controllable steady ramp-up/ramp-down area "; said device is in many cases shortly referenced in the instant document as "switching device".

A detailed view on the individual ramp-up functions at each switching transistor's gate, of the circuit according to **Fig.6**, is shown in **Fig. 4a**. **Vg1** to **Vg7** are the gate

voltage versus tuning voltage slope of the switching stages number 1 to 7 in this example. One can assume for example, said switching transistor's steady change of resistance RDS between very high resistance and very low resistance to be effective between the measured 2 % point and the 98 % point, i.e. the crossing with the 2 % line defines the start point of the steady ramp-up/ramp-down phase and the crossing with the 98 % line defines its end point. All slopes of the individual gate voltages are strictly parallel. Threshold levels **Th1** to **Th7** in **Fig. 4a** may be equally spaced (distances **d1** to **d7** in **Fig. 4a**). **Fig. 4b** visualizes the overlapping switching operations of just 2 adjacent stages of the circuit according to **Fig. 6**. **Overlap** is a measure, where **Vg2** just starts to switch on stage number 2 and where **Vg1** is still operating in the steady transition area (i.e. the RDS steady changing mode) for stage number 1. Because said gate voltage versus tuning voltage slopes are all in parallel, all overlaps are normally the same. Selecting the distance of the threshold levels **Th1** to **Thn** (by properly designing the circuit to generate said threshold levels) also determines the amount of overlap between adjacent switching stages.A translinear amplifier typically has a gain of 1. However, a gain different from 1 is also achievable, which, if implemented, gives one more degree of freedom in dimensioning the overlapping parameters: it allows to change the steepness of the gate control voltage change versus tuning voltage change. Now it is possible to select the switching overlap independent of the switching distance of adjacent capacitor switching stages. For example, the remaining overlapping of neighboring capacitor switching stages may be even further reduced, as the steepness of the steady ramp-up/ramp-down operation can be controlled with adequate selection of the gain. **Fig 4c** demonstrates the reduced overlap of a steeper gate control voltage

Vg1s and **Vg2s** of two adjacent capacitor switching stages, visualized as **Overlap Vg2s - Vg1s**.

There are various techniques for a circuit to generate a set of input and output reference values and to provide the threshold levels to each of said capacitor switching stages. And there are various techniques to provide a suitable input signal, dependent on the tuning voltage, dedicated for the voltage controlled capacitance change, to all of said capacitor switching stages. A conceptual circuit diagram for providing said input reference levels **Ref-in 1** to **Ref-in n** and said output reference levels **Ref-out 1** to **Ref-out n** is shown in **Fig. 6**. As shown in **Fig. 9**, one solution for said circuit to generate a set of input reference values is a simple resistor chain. A possible and minimal, though not the only, solution for a circuit to provide the input threshold levels **Ref-in n** and similarly to provide the tuning voltage **Vtune**, from inputs of said switching control circuit **Switch-Ctrl** to the therin embedded translinear amplifier, is to connect said individual threshold levels, as well as said tuning voltage, with simple wire connections to the appropriate input lines of said translinear amplifier, that is without using further intermittent electronic glue components, as anticipated inside said switching control circuit **Switch-Ctrl** in **Fig. 5** and **Fig. 6**.

Similar to the input reference levels in **Fig. 9**, the output reference levels could be provided for example through a resistor network to provide individual output reference levels for each translinear amplifier (**Ref-out-1** to **Ref-out-n**). Another possible and a minimal solution, providing an identical output reference level to all translinear amplifiers, could be to connect all output reference points of all translinear amplifiers

(equivalent to **Ref-out-1** to **Ref-out-n** in **Fig. 6**) to a common output reference level **C-Ref-out**, as it is shown in **Fig. 9**.

Another key point of the invention is the implementation of signal cutoff functions at both ends of the steady ramp-up/ramp-down area. At the end-points of said steady transition area, where further linear change of the switch control signal **Vsw** would have nearly no further effect on the switching device to change its resistance RDS. After passing said end-points of said steady transition area, it would be desirable to not continue with a linear signal to control the switching device, but to apply a very steep signal change, thus driving the switching device very sharply into its minimum achievable resistance (RDSon as low as possible) or into its maximum achievable resistance (RDSoff as high as possible). Two additional circuits, **CutOffC-Lo** and **CutOffC-Hi** in **Fig. 10a**, perform said steep signal change, where one of said two additional circuits takes over full control of the switch control signal **Vsw,** i.e. they "override" the normal control signal, as provided by the translinear amplifier itself. The end-points of said steady transition area, where the steep signal change should appear are called the cut-off edges. Which of said two additional circuits is activated, depends on the switch status: to drive the switching device into minimum achievable resistance (RDSon as low as possible), the additional cut-off circuit **CutOffC-Lo** will be activated, or to drive the switching device into its maximum achievable resistance (RDSoff as high as possible) the additional cut-off circuit **CutOffC-HI** will be activated

Fig. 7b of the instant document visualizes the idea of sharply cutting off said signal controlling the switching device as soon as a changing Gate Control Voltage **Vg**

leaves the desired steady transition area **Steady ramp-up/ramp-down Area** at the cutoff edges **CutOff Lo** and **CutOff Hi**. For example, at the two desired points, beyond the 98 % on-point, said signal **Vg** controlling the switching device is rised sharply and below the 2 % on-point said signal **Vg** controlling the switching device is driven to rapidly switch-off. The area outside the desired steady transition area at the low (RDSon) resistance side of said switching device is marked **Outside Lo,** and the area outside the desired steady transition area at the high (RDSoff) resistance side of said switching device is marked **Outside Hi**. The end-points **Ep-Lo** and **Ep-Hi** in **Fig. 7a** correspond with the cutoff edges marked with **CutOff Lo** and **CutOff Hi**

A possible solution for said signal cutoff functions could be to implement said signal cutoff functions as separate circuits in combination with, but external to said translinear amplifier. The principal concept of said two separate circuits for said signal cutoff functions is shown in **Fig. 10a**, with the two signal cut-off circuits **CutOffC-Lo** and **CutOffC-Hi** added to said (main) circuit to control the switching operation **Switch-Ctrl** of **Fig. 5**. These three circuits then operate together (possibly similar in function to a dotted-OR connection of said three circuits) to provide a combined control signal **Csw** for said switching device **SW**; Each cut-off circuit can thus override the output of the normal **Switch-Ctrl** circuit, once the switching device **SW** leaves the desired steady ramp-up/ramp-down area. Appropriate threshold elements will define the limits **CutOff Lo** and **CutOff Hi** of the steady ramp-up/ramp-down area, as shown in **Fig. 7b** and as explained above. Said possible threshold elements then provide the two control signals to either force said fully on or fully off state are **CtlCutOff Lo** and **CtlCutOff Hi**,

Another possible solution could be to implement said signal cutoff functions within said translinear amplifier circuit. Such solution integrated into the translinear amplifier is presented in Patent Application US Serial No. 10/676919, filed Oct. 1, 2003, which is hereby incorporated by reference. The relevant additional signal cutoff function is presented there on page 6, 3rd and 4th paragraph, on page 14, 1st and 2nd paragraph, page 15 2nd full paragraph, on page 17, 1st and 2nd paragraph and in **Fig. 7** with the additional circuits **ADD-COMP 1-7** and **ADD-COMP 2-7**. Circuit **ADD-COMP 2-7** in the referenced companion application is a real implementation of a cut-off circuit **CutOffC-Lo** in **Fig. 10a** of the instant application and circuit **ADD-COMP 1-7** in the referenced companion application provides the control signal defined as **CtlCutOff Lo** in the instant application. The referenced application describes the implementation of the signal cutoff functions as cited in the following paragraph:

The envisioned solution is described in the first full paragraph on page 14 in the referenced Patent Application US Serial No. 10/676919 (and paragraph [0043] in the now issued Patent): "According to said second aspect, two additional circuit functions sharply limit the analog operating region through an extra current limiting transistor on one side and the purposely use of the voltage limited by the power supply on the other side. Key objective is to linearly control said translinear amplifier's output, for example for switching on or off a transistor in an application like it is shown in **Fig. 4** (of the referenced patent application), and getting sharp cutoff edges, for example for switching on or off a transistor in said application to achieve minimum RDSon and maximum of RDSoff at the extreme ends. The desired output characteristic is visualized in **Fig. 5** (of the referenced patent application)."

Further explanation of the additional circuit is found in the first paragraph on page 17 in the referenced Patent Application US Serial No. 10/676919 (and paragraph [0051] in the now issued Patent): "**Fig. 7** (of the referenced patent application) shows the circuit of **Fig. 6** with the additional limiting transistor function, where the additional components are shown inside the dashed frames, marked with **ADD-COMP 1-7** and **ADD-COMP 2-7**. According to said second aspect of this invention, two additional circuit functions sharply limit the analog operating region through an extra current limiting transistor on one side and the purposely use of the voltage limited by the power supply on the other side. Transistor **N13-7** incorporates said current limiting transistor. (.....) As soon as the current drawn by **N13-7** exceeds the current provided by **N8-7**, **N13-7** sinks all available current and the output is cut-off."

And even further in the second paragraph on page 17 in the referenced Patent Application (and paragraph [0052] in the now issued Patent): "Similar, when the output voltage **Voutp-7** swings to **Vdd**, further voltage increase is suddenly impossible, thus sharply limiting said linear operation region" in the desired way.

The specific implementation of the signal cutoff function integrated within said translinear amplifier of the referenced application takes advantage of the fact, that the output signal can completely swing up to the power supply rail, driving the Gate-Source Voltage of the switching device to zero, thus forcing a PMOS switch to go into high impedance state without any further measures. In case the output signal could not swing up to the power supply rail or if a different type of switching device is used, an

additional circuit similar in function to the circuits **ADD-COMP 1-7** and **ADD-COMP 2** would be implemented.

Fig. 8 presents the same behavior as **Fig. 7b** for a larger number of said capacitor switching stages. **Th1** to **Thn** are the selected threshold for said switching to occur. **d1** to **dn** are the distances of said threshold, that normally are dimensioned to equal distance. The capactitor tuning voltage **Tuning Voltage Vctl** is supplied to all capacitor switching stages as a common signal.

Fig. 9 shows a realistic circuit diagram of an implementation, in accordance with an embodiment of this invention. **Tr.Amp 1** to **Tr.Amp n** are said translinear amplifiers, **Sw 1** to **Sw n** are the switching devices and **Cap 1** to **Cap n** are said capacitors that will be switched in parallel, resulting in the total capacitance **varCap**. **R1** to **Rn** build the resistor chain to produce references voltages for the amplifier of each stage, as an implementation of the reference circuit shown in **Fig. 6**. Similar to **Fig.6**, the combination of one translinear amplifier **Tr.Amp k**, combined with adequate control circuit and one switching device **Sw k** could be considered as an individual capacitor switching stage, where one of said capacitor switching stages connects to one capacitor **Cap k** out of a set of small capacitors. Each of said capacitor switching stages is controlled through the common input **Vtune** and an individual input reference level **Ref-in k**. In the implementation shown in **Fig. 9**, the output reference signals **Ref-out k** of

Fig. 6 are all connected to a common output reference signal **C-Ref-out**. All of these stages k = 1 to n have basically identical functional characteristics.

Furthermore, a concept of this disclosure is to compensate the temperature deviation, caused by the temperature characteristics of the switching device; **Fig. 10b** presents this concept, which shows a temperature compensating circuit **Temp-Comp** in addition to said circuit to control the switching operation **Switch-Ctrl**, as shown in **Fig. 5**. One method is to use a device **N2-10** of the identical type of the switching device **N1-10** to produce a temperature dependent signal. A temperature compensating voltage, produced by said device **N2-10**, is added to the output reference signal **Ref-out-10**, now resulting in a temperature compensated output reference signal **Ref-out-c-10.** The input of said temperature compensating circuit **Temp-Comp** is connected to one of the output reference signals of the common reference circuit **RefCirc** of **Fig. 6** and it's the output of said temperature compensating circuit **Temp-Comp** then provides a compensated signal to the output reference point **Voutn-10** of the translinear amplifier. This compensation technique will mirror the exact equivalent of the temperature error into the switching control signal **Vg** and compensate its temperature error. The output reference point **Voutn-10** in **Fig. 10b** is the same point as the reference signals **Ref-out** in **Fig. 5**. Within each a set of multiple capacitor switching stages, there is one of said temperature compensating circuits.

As already described with **Fig. 9**, a simplified solution providing an identical output reference level to all translinear amplifiers could be to connect a common signal to all output reference points **Ref-out** (equivalent to **Voutn** of the translinear amplifiers) in common. In the case of providing an identical temperature compensated reference voltage as a common signal, it would be sufficient to implement a single temperature compensating circuit to serve all said output reference points **Ref-out** in common. **Fig. 10c** presents such simplified and common temperature compensating circuit.

The total capacitance versus tuning voltage characteristic for a circuit with n-stages is demonstrated in **Fig. 11a** and the overall characteristic of said Q-factor is presented in **Fig. 11b**.

Typically, it would be desirable to achieve a linear relation between the tuning voltage and the capacitor variation, i.e. in a strictly linear mode. Then the reference voltages to compare with the tuning voltage would normally be equally spaced. However, to achieve a steady, but predefined non-linear relation instead, other reference voltage steps for said threshold levels could also be selected, like spacing along a parabolic curve. As explained before, one circuit example is said resistor chain **R1** to **Rn**, or a similar circuit, to produce a series of voltage references **Ref 1** to **Ref n**, where each of said translinear amplifiers compares the tuning voltage with its dedicated reference voltage. To achieve a non-linear relation between threshold levels and tuning voltage, a set of reference voltages will be provided, that are, instead of being equally spaced, spaced along a desired non-linear curve. As one suggested embodiment, such non-linear relation can be achieved by appropriate selection of the values of said

resistor chain **R1** to **Rn.** Similar, the tuning voltage could be split into a multiple of tuning signals to feed them to the translinear amplifier inputs. Depending on the technique to implement the reference values defining said threshold levels for each of the translinear amplifiers within said *chain of said* capacitor switching stages, specific nonlinear relations of capacitance change versus tuning voltage can be constructed. The concept of said non-linear relation is demonstrated in **Fig. 12**, with **Curve A** and **Curve B** as examples.

In accordance with the objectives of this invention, a set of individual capacitors is implemented. Such capacitors could be metal or polymer capacitors, eventually mounted or fabricated on a common planar carrier or they could be integrated on a semiconductor substrate. The advantage of a capacitor not being of the junction (diode) type capacitor is the invariance due to voltage or temperature at the capacitor. The switching device is typically a FET transistor, which could be for example a P-channel or N-channel junction FET or a PMOS or NMOS FET. In the case complementary components are used all voltage levels would just be inverted without changing the principals of operation.

The method to achieve the objectives of this invention is illustrated in **Fig. 13**. First **(80)**, it starts with just the first capacitor, i.e. the count n=1 **(81)**. When the tuning voltage is rising **(82)** or is high enough **(83)**, the amplifier ramps up **(85)** and the switching device linearly switches on capacitor element n **(87)**. If the tuning voltage

continues to rise **(90)** the amplifier continues to ramp up **(91)**. If however the tuning voltage turns down **(90)**, the amplifier will ramp down as well **(92)**. Once the tuning voltage reaches the upper limit of the steady transition area **(95)**, the switching device of stage n is fully switched on **(97)** and the process continues with the next step n = n + 1 **(99)(101)**. Depending on the direction of continued voltage change **(103)** it continues to ramp up or down. In case tuning voltage is lower than maximum for stage n **(84)**, the amplifier ramps down **(86)** and the switching device linearly switches off capacitor element n **(88)**. Once the tuning voltage reaches the lower limit of the steady transition area **(96)**, the switching device of stage n is fully switched off **(98)** and the process continues with the next step n = n - 1 **(100)(102)**. Again, depending on the direction of continued voltage change **(103)** it continues to ramp up or down and restarts at **(82)**.

While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made without departing from the spirit and scope of the invention.